A Synchrotron-Based Fourier-Synthesis Custom-Coherence Illuminator

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In collaboration with the Virtual National Laboratory

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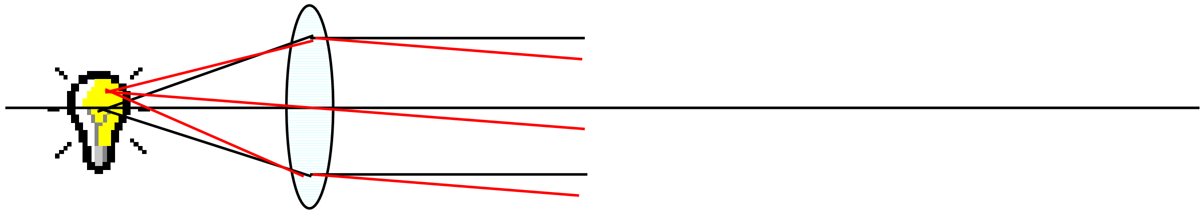
Outline

- **Overview of spatial coherence**
- **Issues with coherence and lithography at the ALS**
- **Fourier-synthesis illuminator**
- **Lithographic demonstration of coherence control**

What makes a source incoherent?

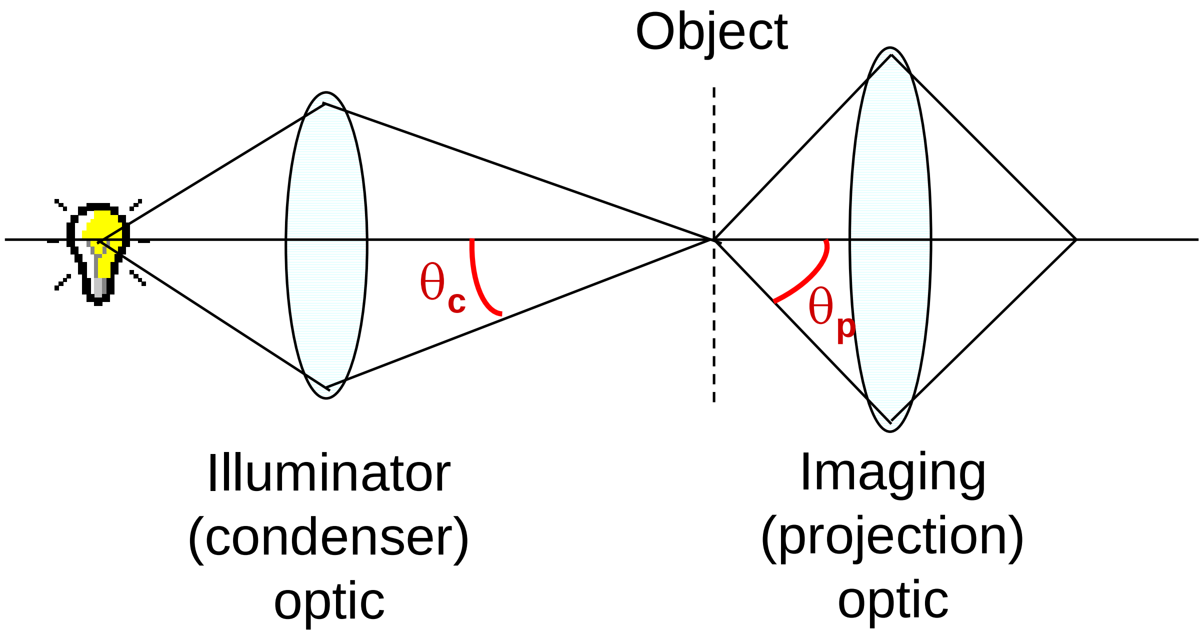
- In real space, a low-coherence source can be thought of as a source with many independent point radiators
- The frequency-space equivalent description is a source with many independent plane-wave radiators



Köhler illumination

- "independent" means unable mutually incoherent (add in field).
  - Thus illumination divergence is a necessary but not sufficient condition for reduced coherence
  - "independence" can be guaranteed be ensuring that the "source elements" do not coexist in time

Optimal imaging performance generally requires illumination partial coherence (σ>0.5)



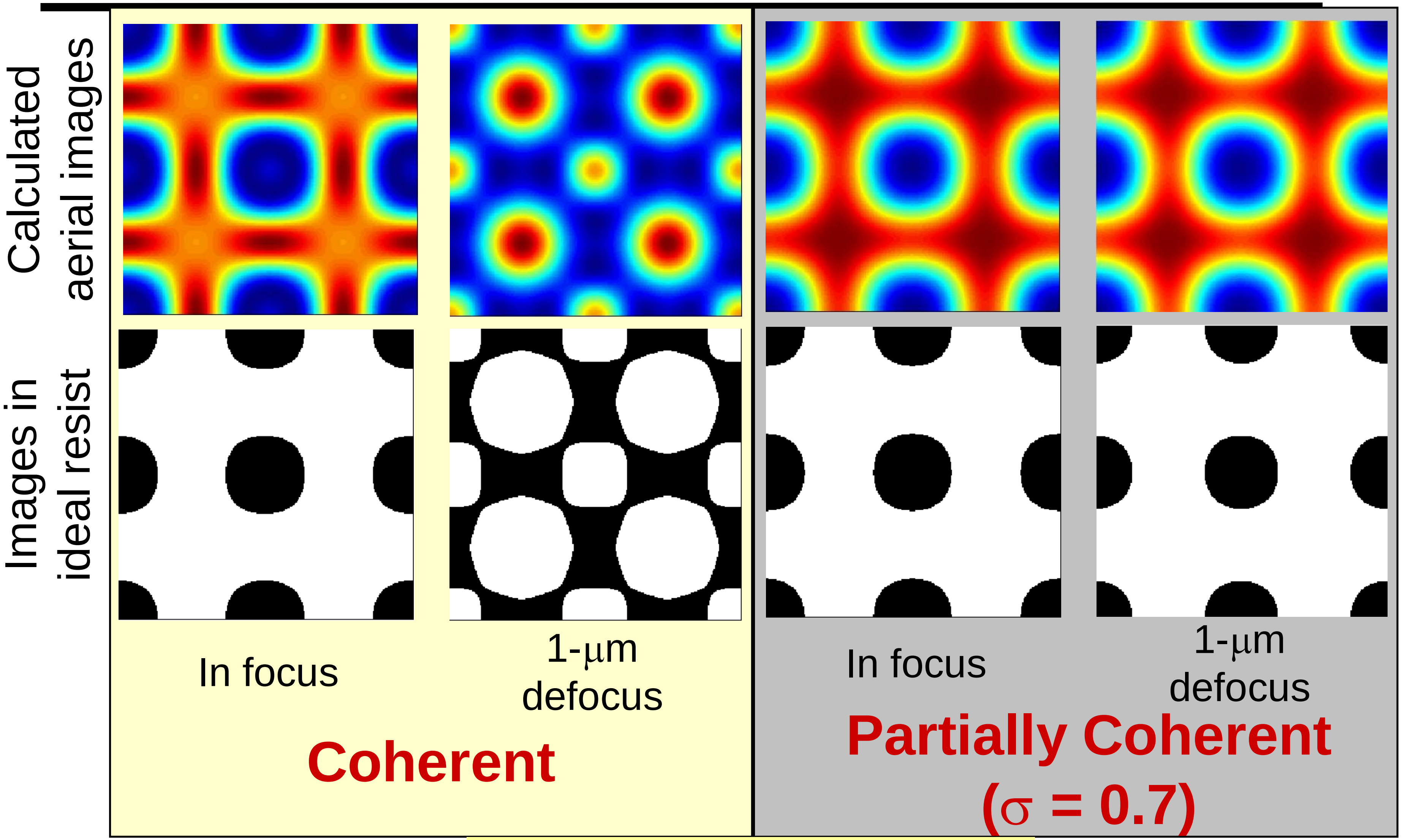
$$\sigma = \theta_c / \theta_p$$

Specific case of critical illuminator with incoherent source

$$\sigma = \mathit{Res} / L_c$$

Generally, σ is ratio of imaging optic resolution to illumination coherence width

Coherent illumination extremely susceptible to phase errors



100-nm contacts imaged with 0.1-NA system at λ = 13.4nm

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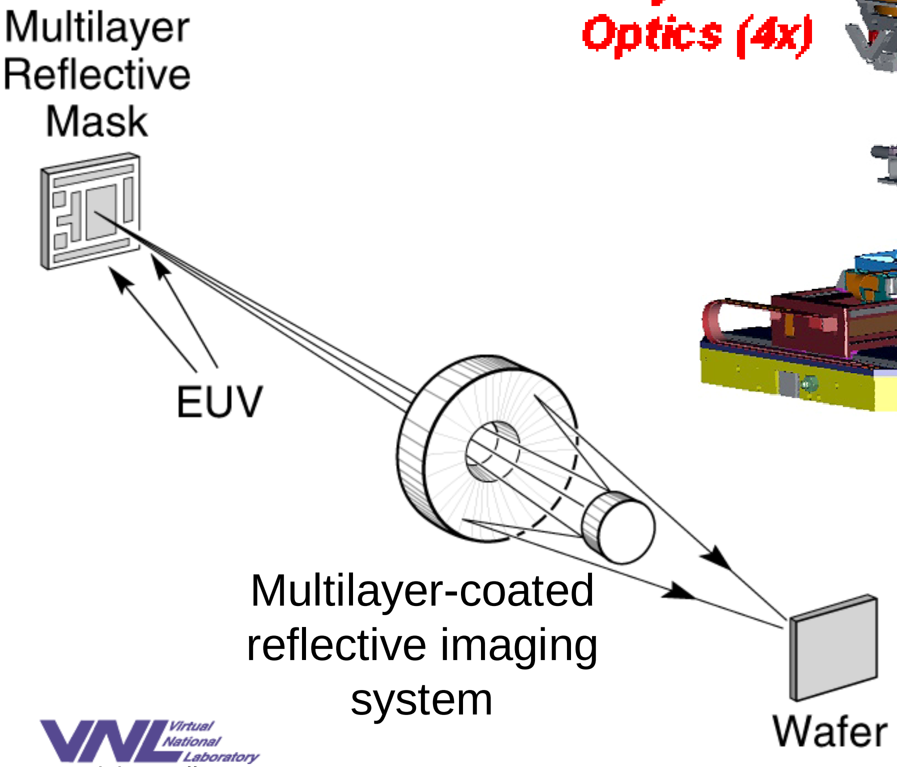
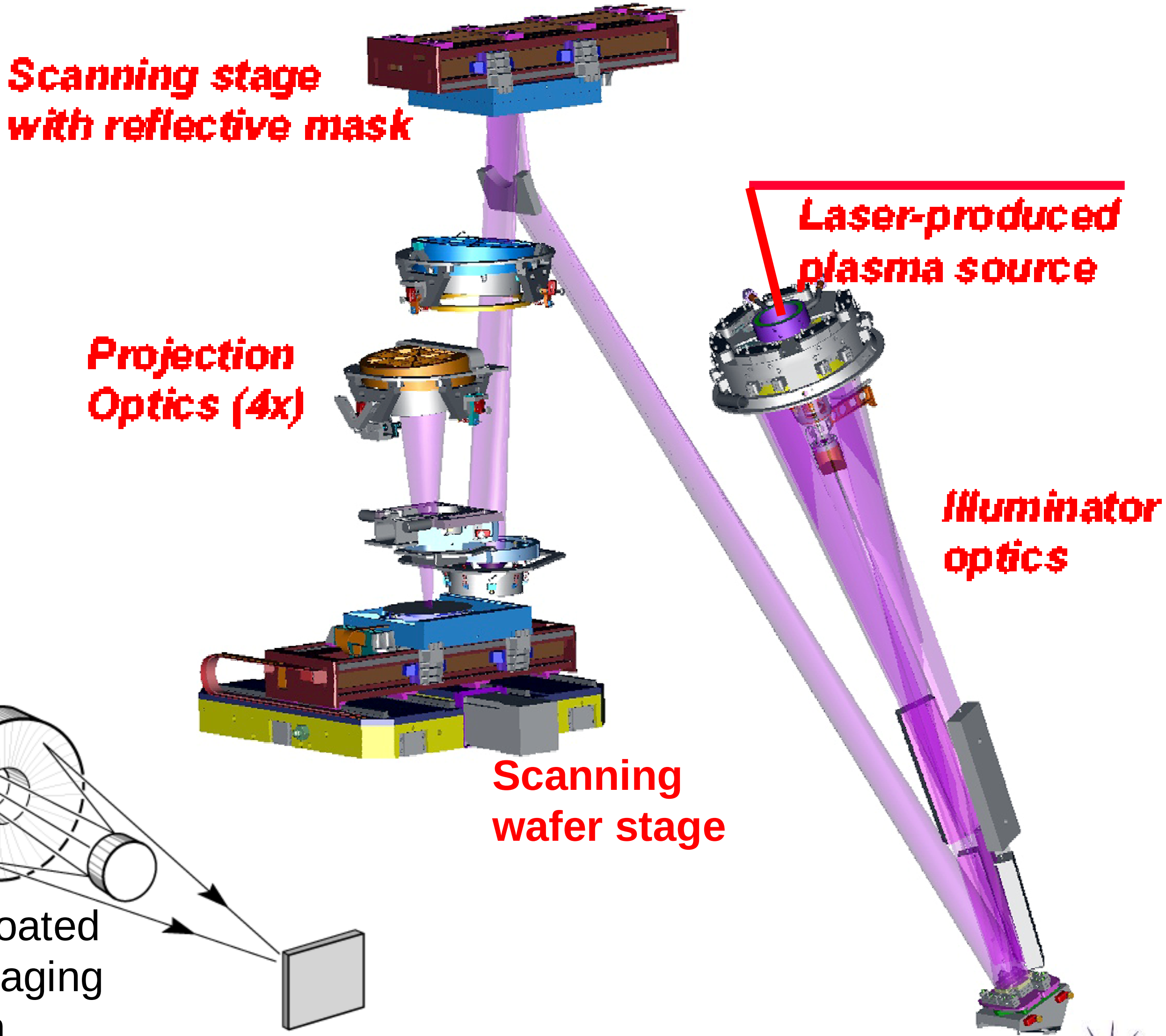
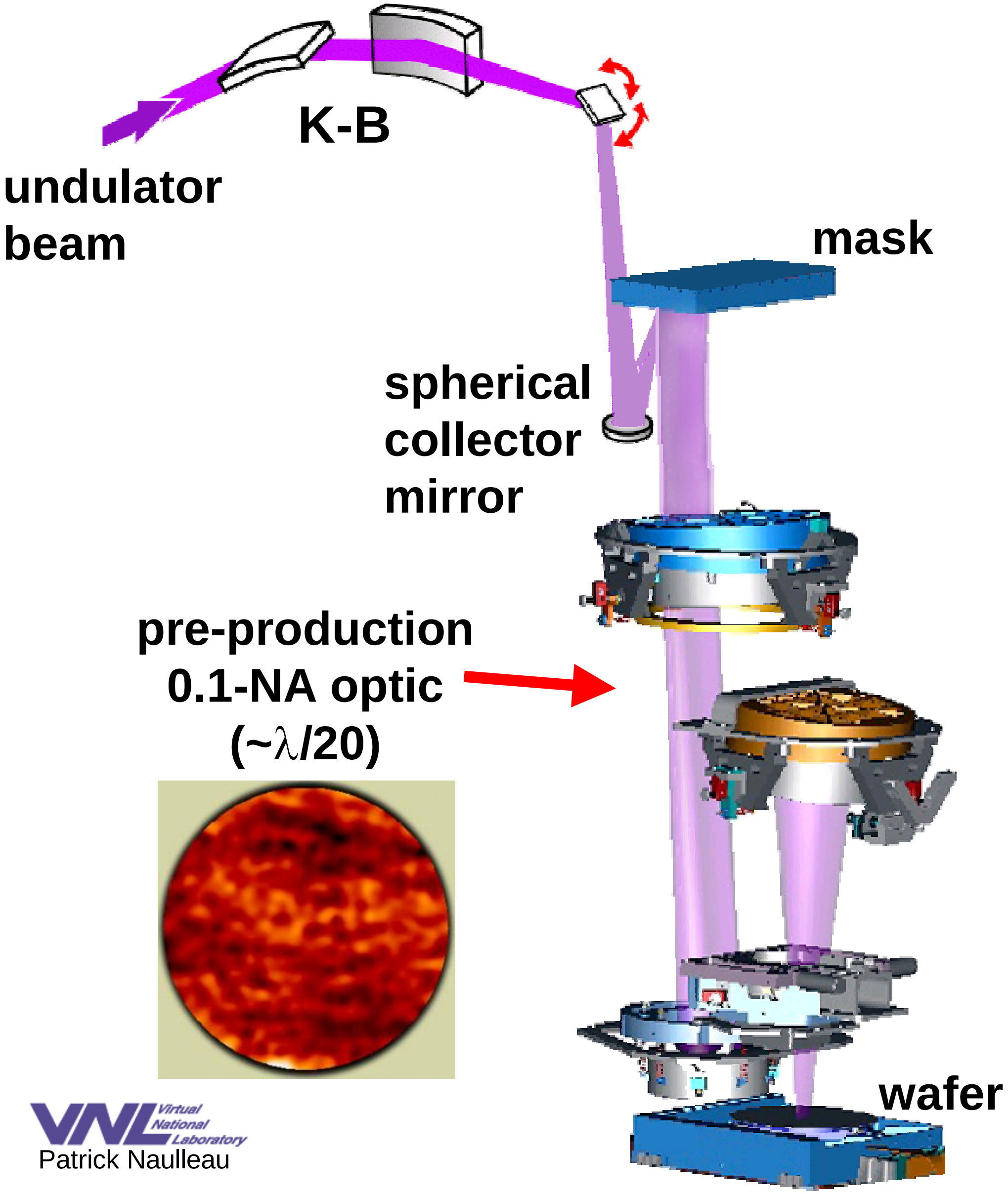
What is EUV lithography?





Synchrotron-based advanced lithography tool at the ALS



- Static imaging in 100 μm subfield at wafer.
- Cover full static arc-field subfield-by-subfield.
- Use standard EUV reflection masks.
- 0.1-NA pre-production, diffraction-limited optic
- operating wavelength = 13.4 nm

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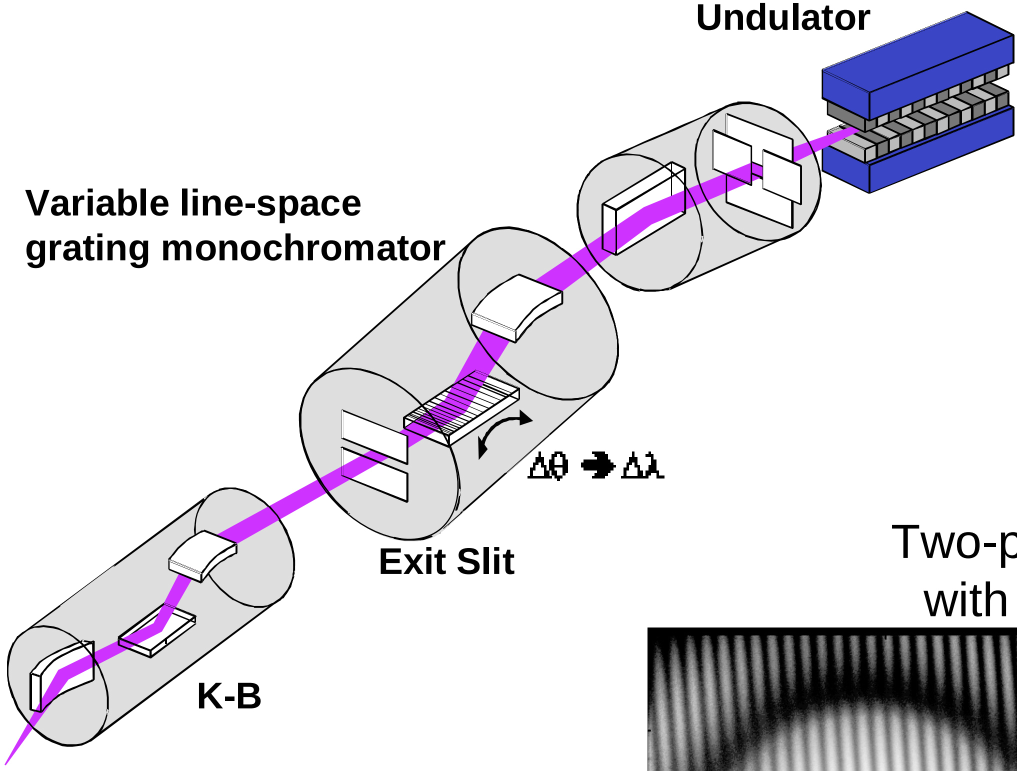
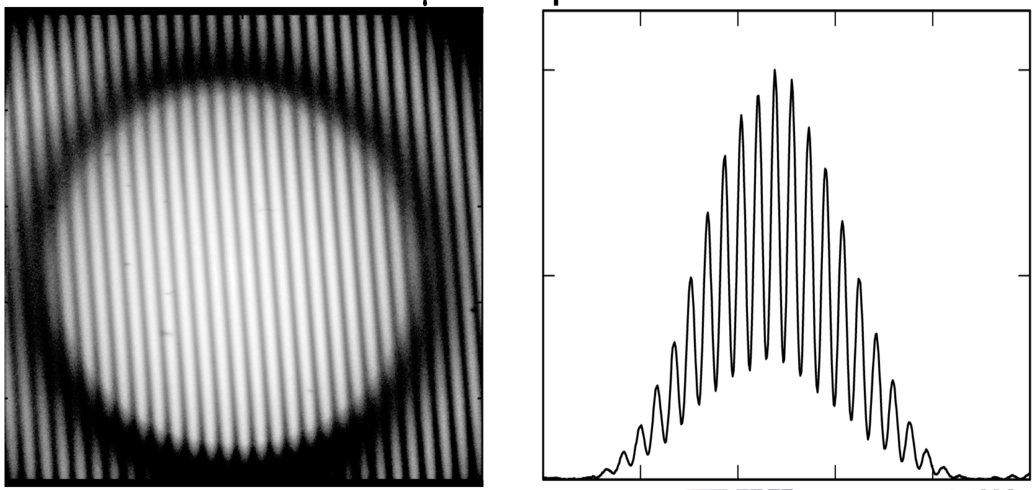
Relevant lithography requires undulator-beam coherence to be reduced



Full beam width
~ 10 μm

- Measured coherence ~ 7 μm
- Object Res = 0.4 μm
- $\sigma \approx 0.4/7 = 0.057$
- intrinsic coherence ~10x too high

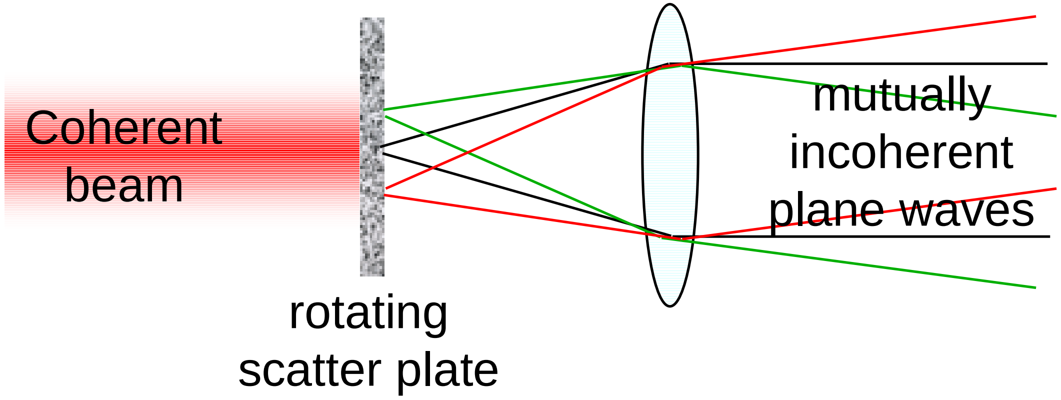
Two-pinhole interference
with 5 μm separation*



*** C. Chang, *et al.***

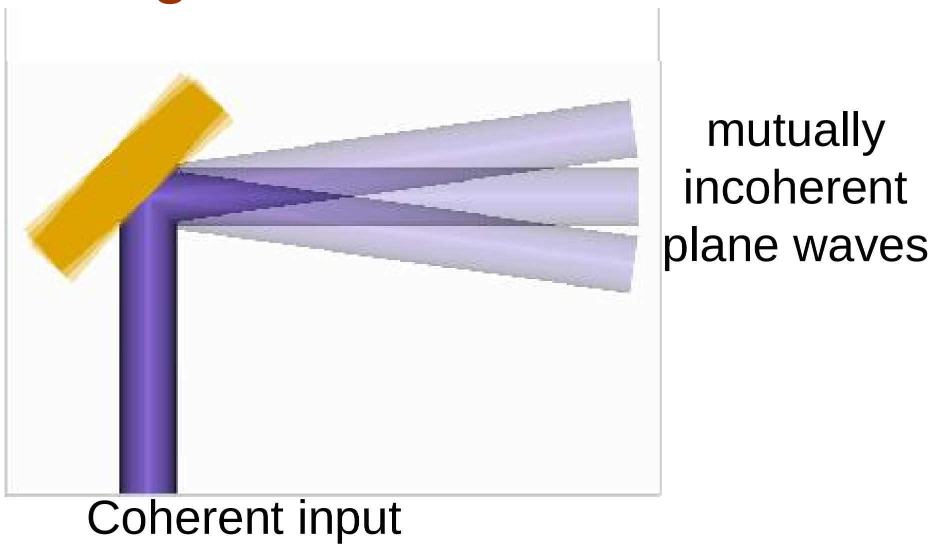
Reducing coherence

Scatter plate



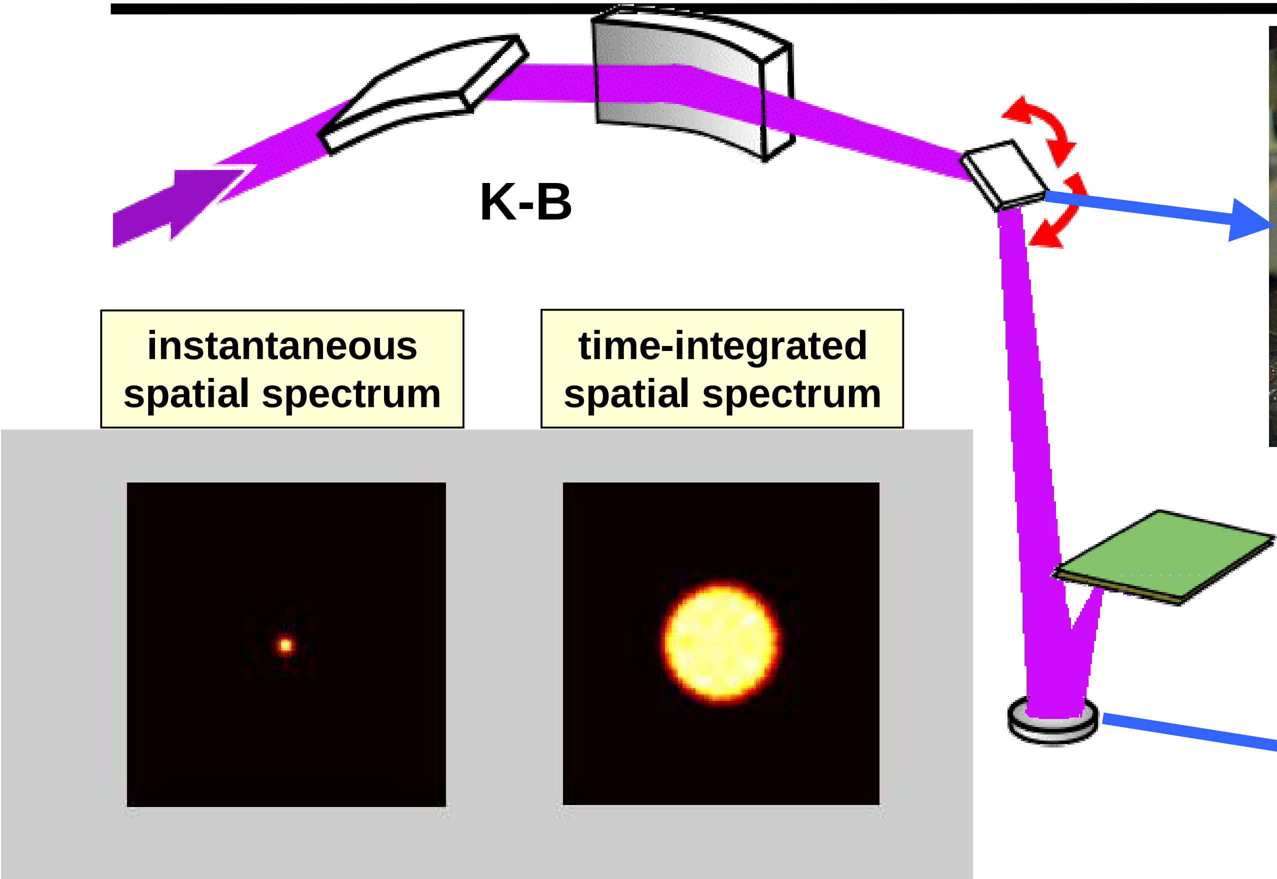
- **Method often used at visible wavelengths**
- **Difficult to implement and low efficiency in EUV and Soft-X-Ray regime**

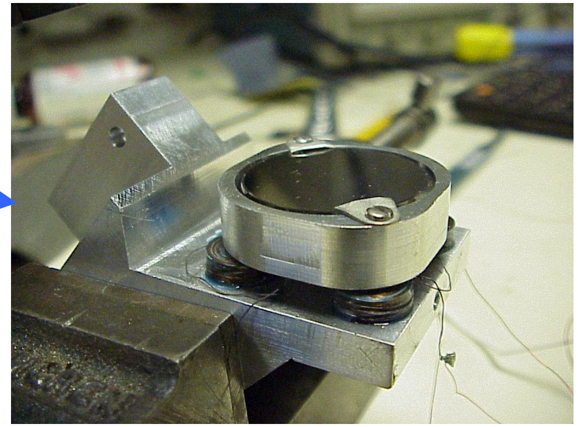
Scanning illuminator



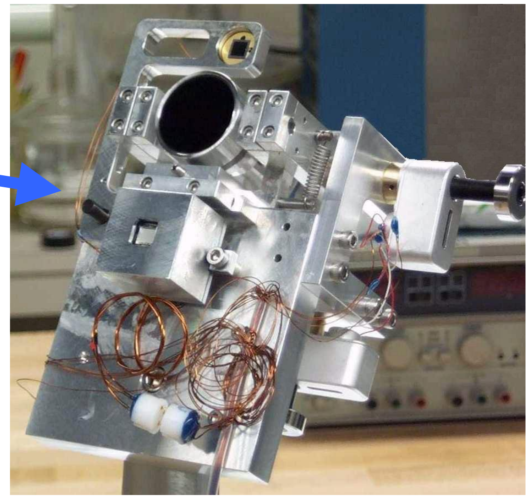
- **Readily implemented at short wavelengths**
- **High efficiency**
- **Facilitates programmable coherence capability**

Programmable scanning illuminator implemented in ALS lithography tool





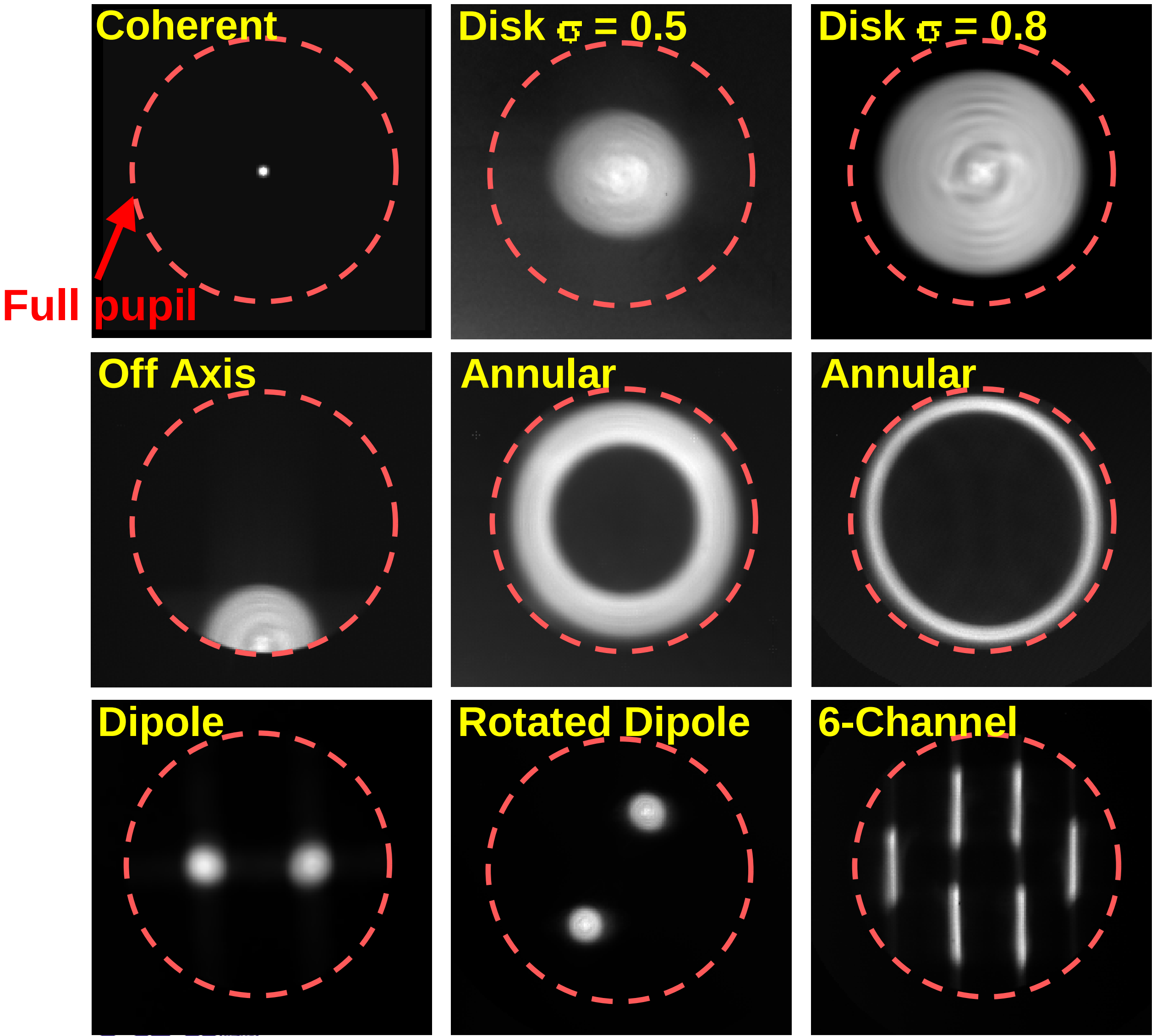
In vacuum 2D angle scanner



Collector assembly

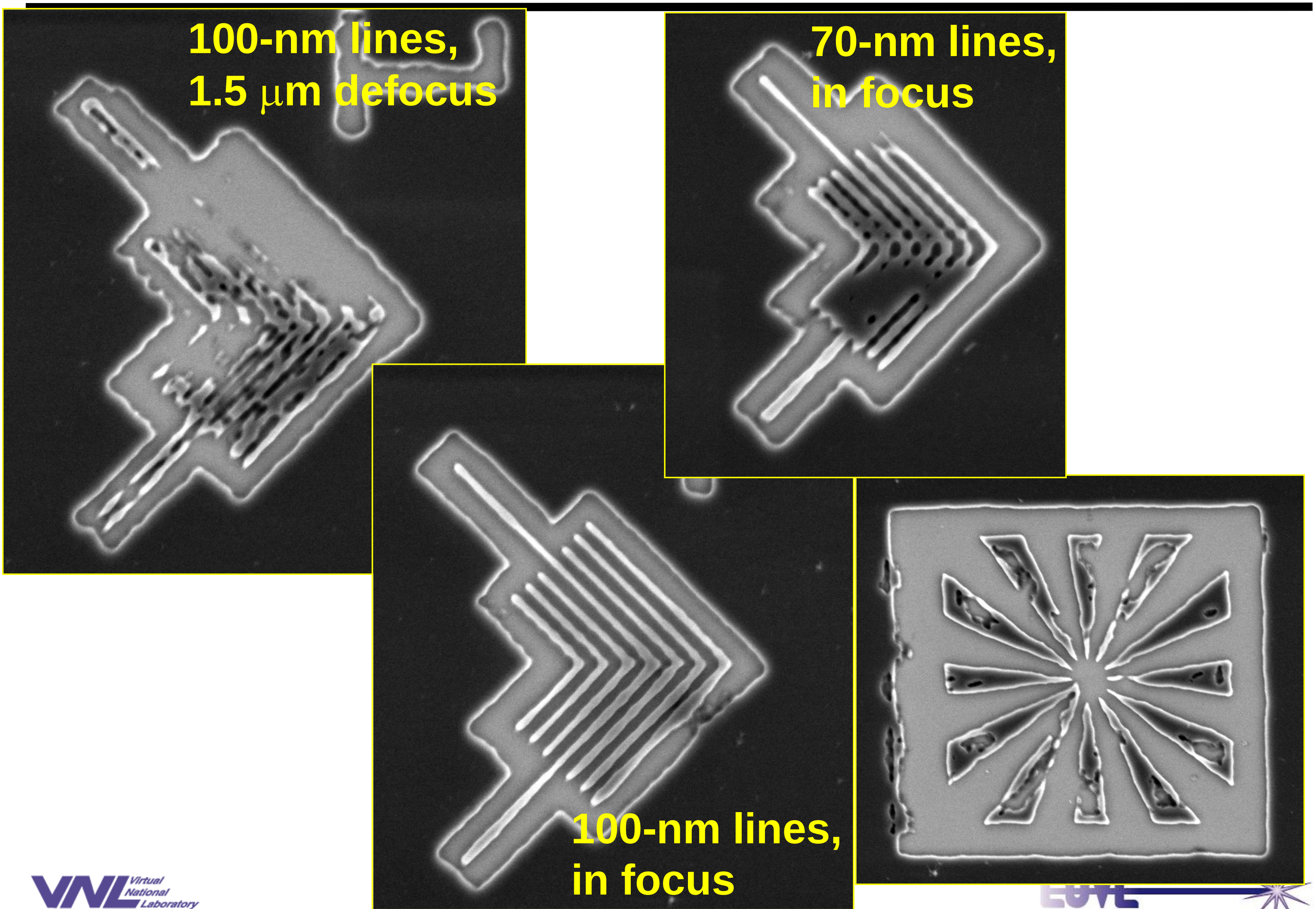
- Scanning illuminator enables in situ control of illumination partial coherence
- Enables arbitrary spectra (coherence functions) to be generated.

Illuminator-generated EUV pupil fills recorded using in situ CCD-based pupil-fill monitor

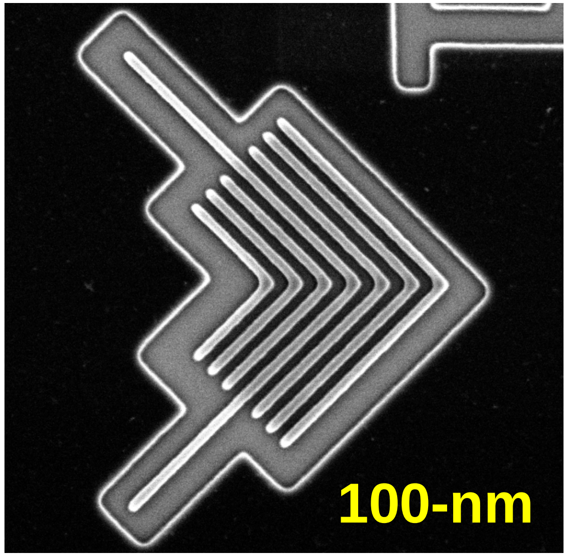


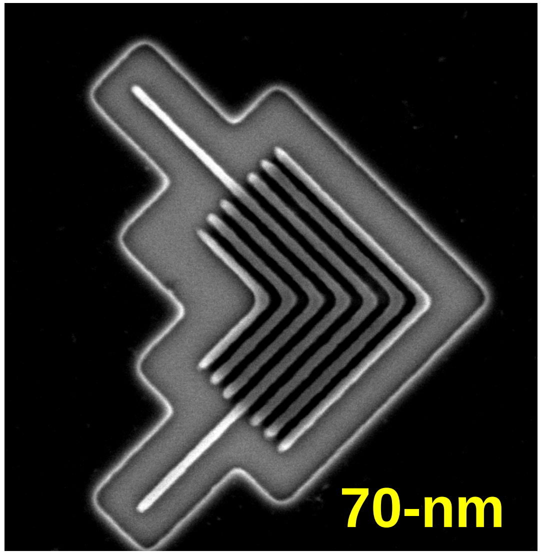
- **Critical illumination**
- **Pupil fill is visualization of source spatial spectrum**
- **Source spectrum and spatial coherence form Fourier-transform pair**

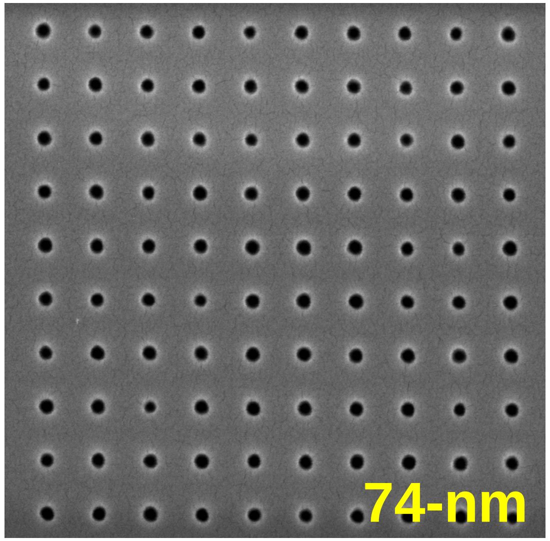
Interference effects limit the usefulness of coherent illumination for lithography

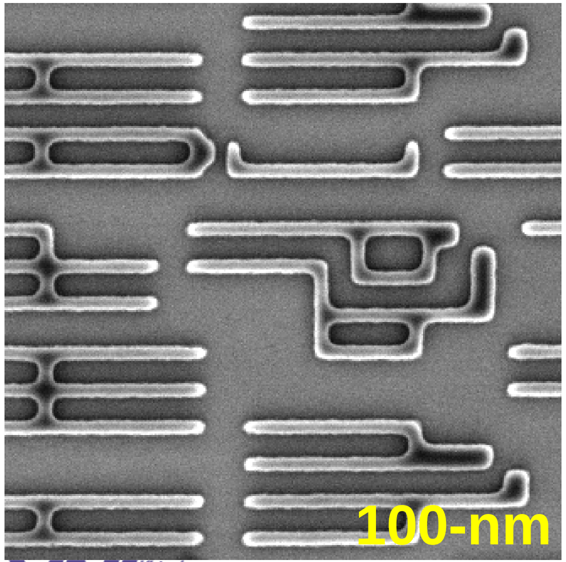


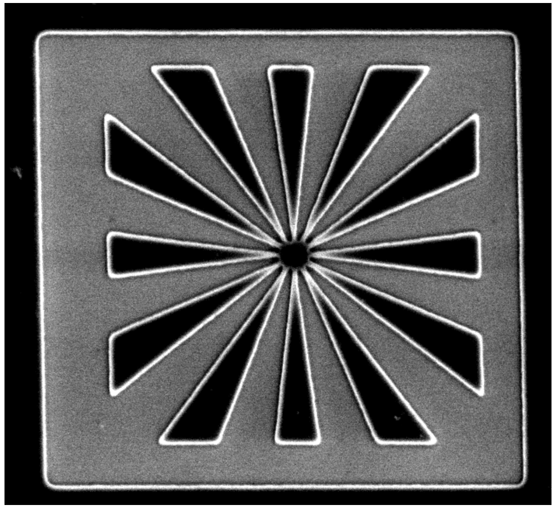
Partially-coherent illumination ($\sigma = 0.7$) dramatically improves performance

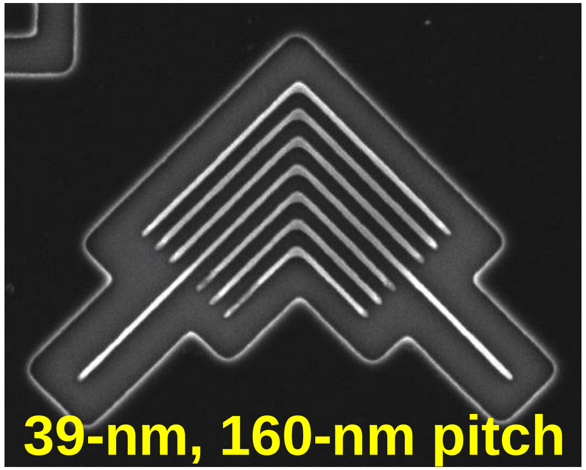












Direct comparison of coherence vs partial coherence near coherent resolution limit

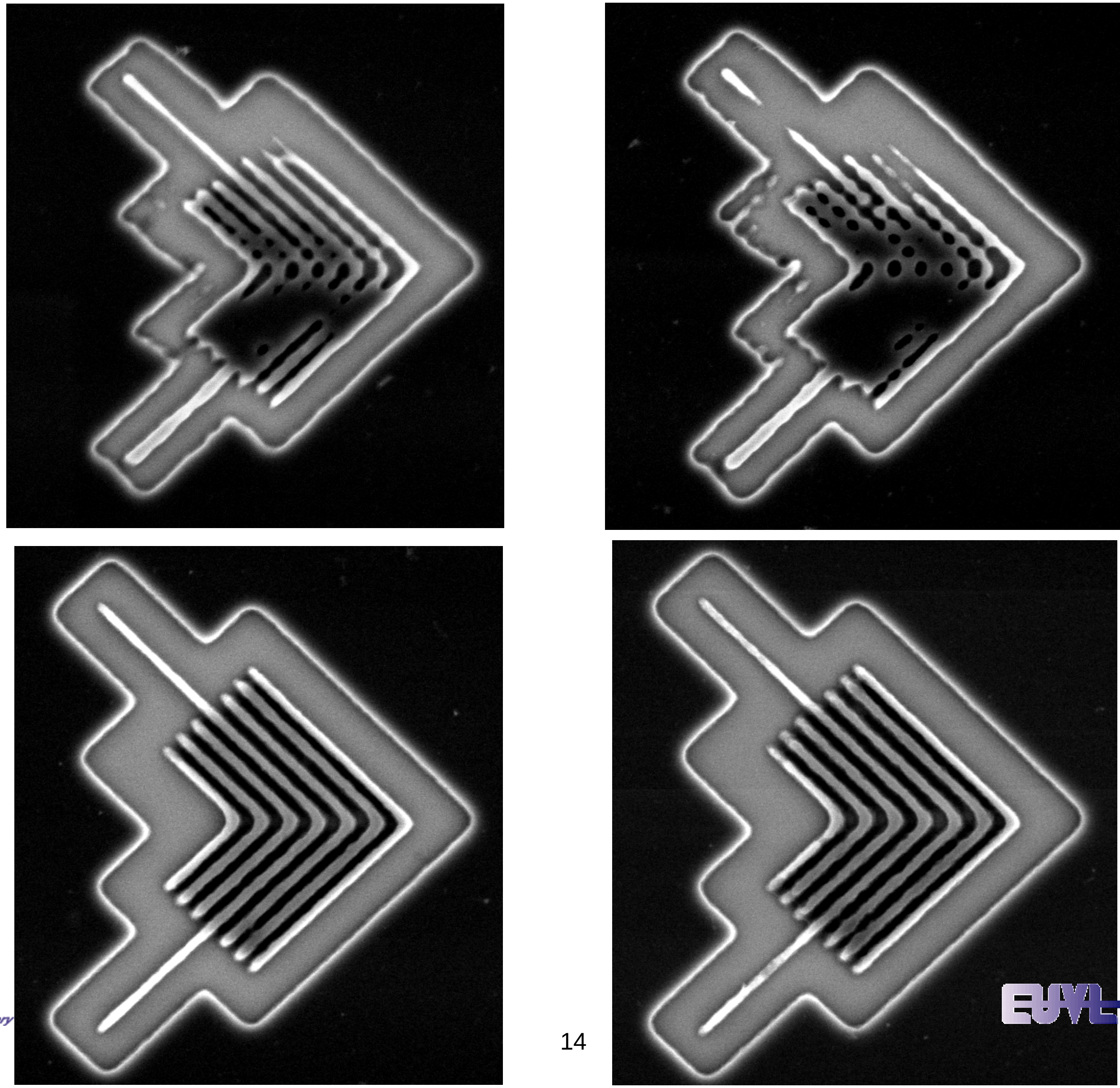
In focus

-0.5-um defocus

70-nm features

Coreherent

$\sigma = 0.7$



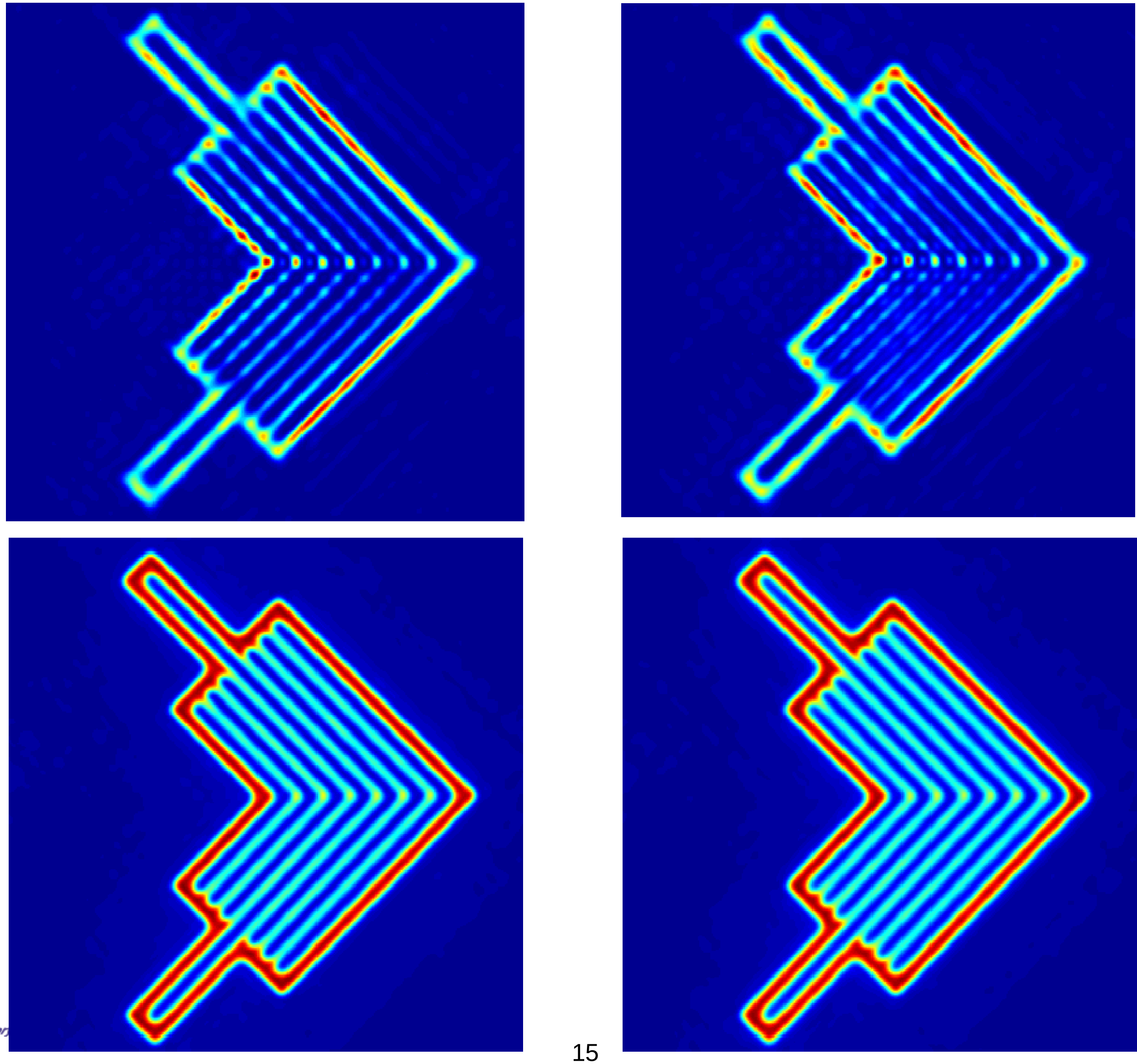
Modeling results consistent with printing

70-nm features

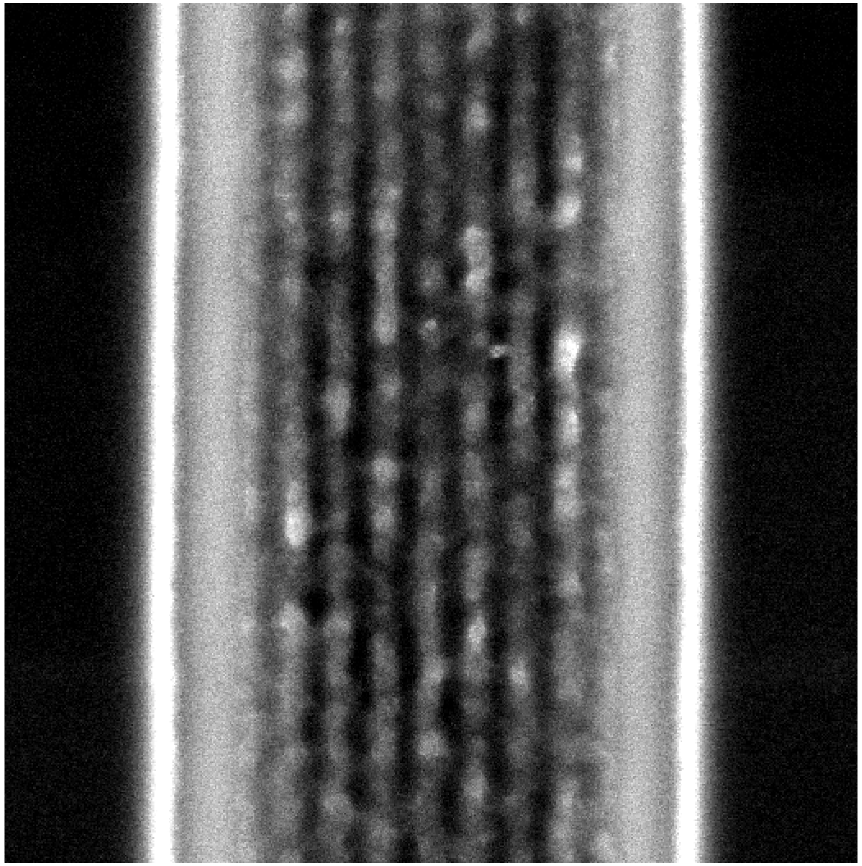
In focus | -0.5-um defocus

Coreherent

σ = 0.7

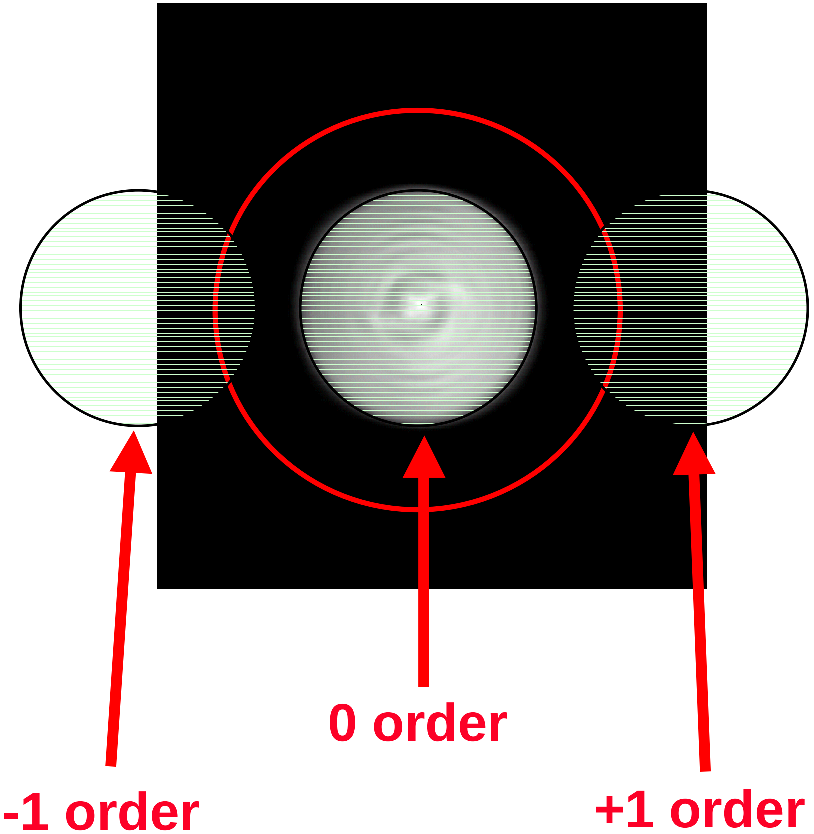


50-nm lines and spaces well beyond conventional Rayleigh limit



50-nm lines and spaces

Pupil image for 50-nm lines under conventional σ = 0.7 illumination



Rayleigh limit = (0.61λ)/NA = 82 nm

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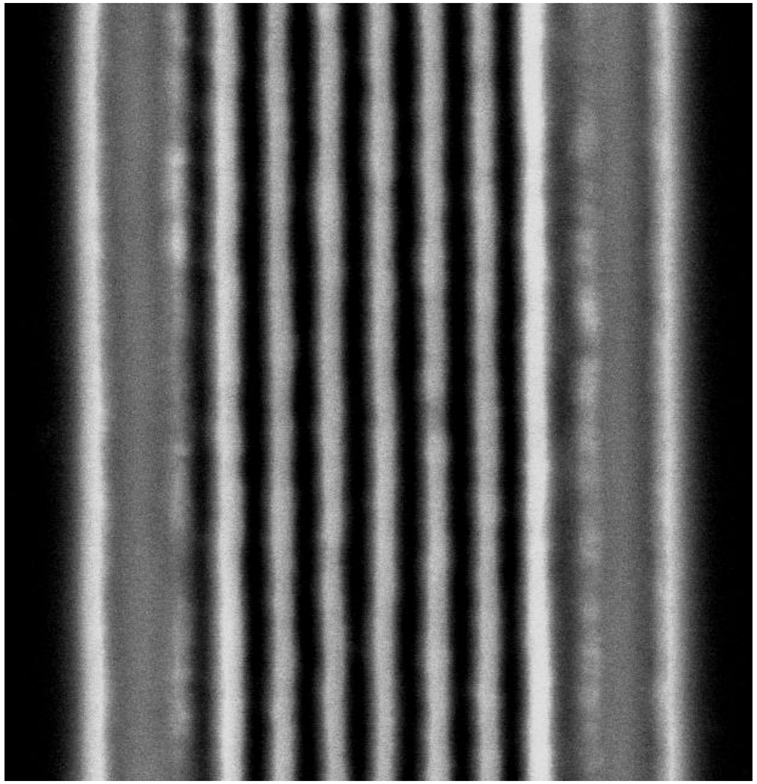
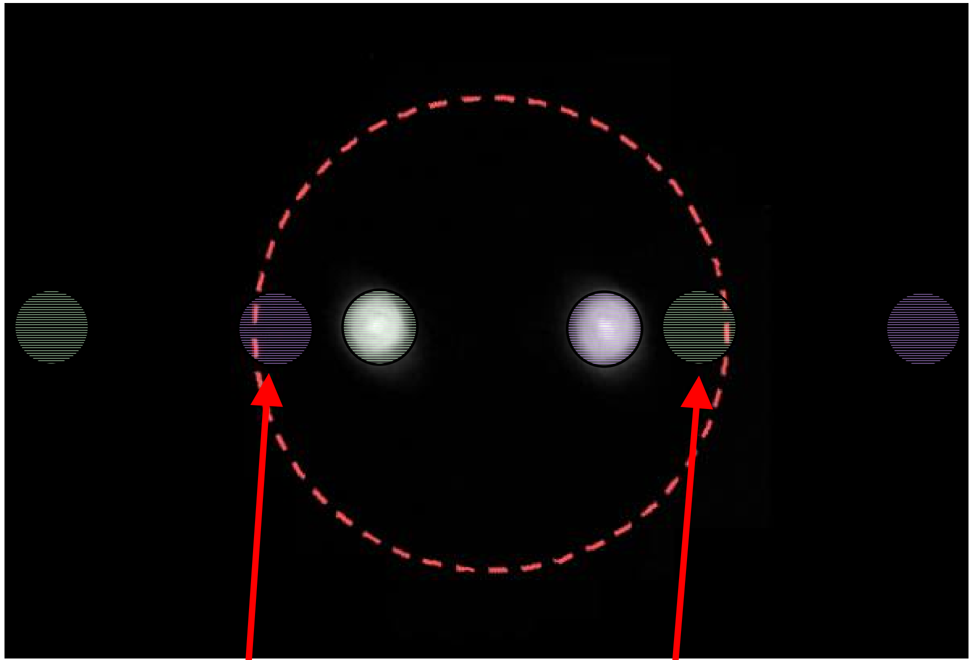
Dipole illumination enables Rayleigh limit to be surpassed



50-nm lines and spaces

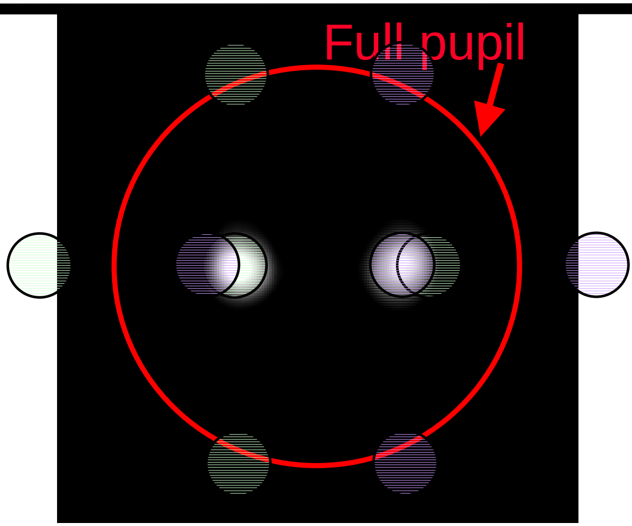
Pupil image for 50-nm lines under dipole illumination

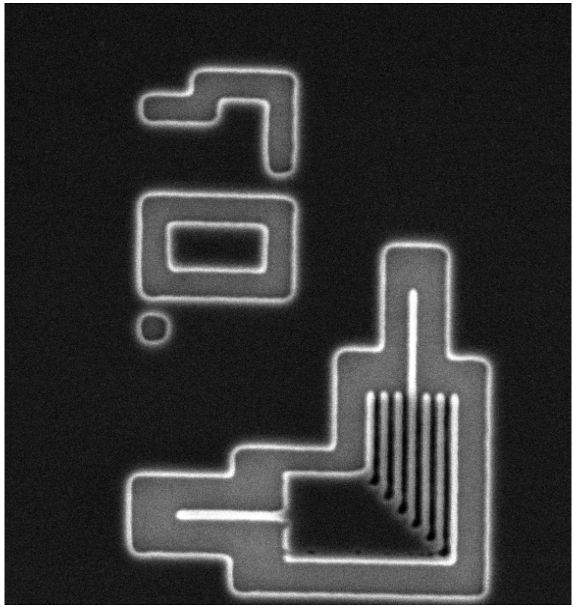


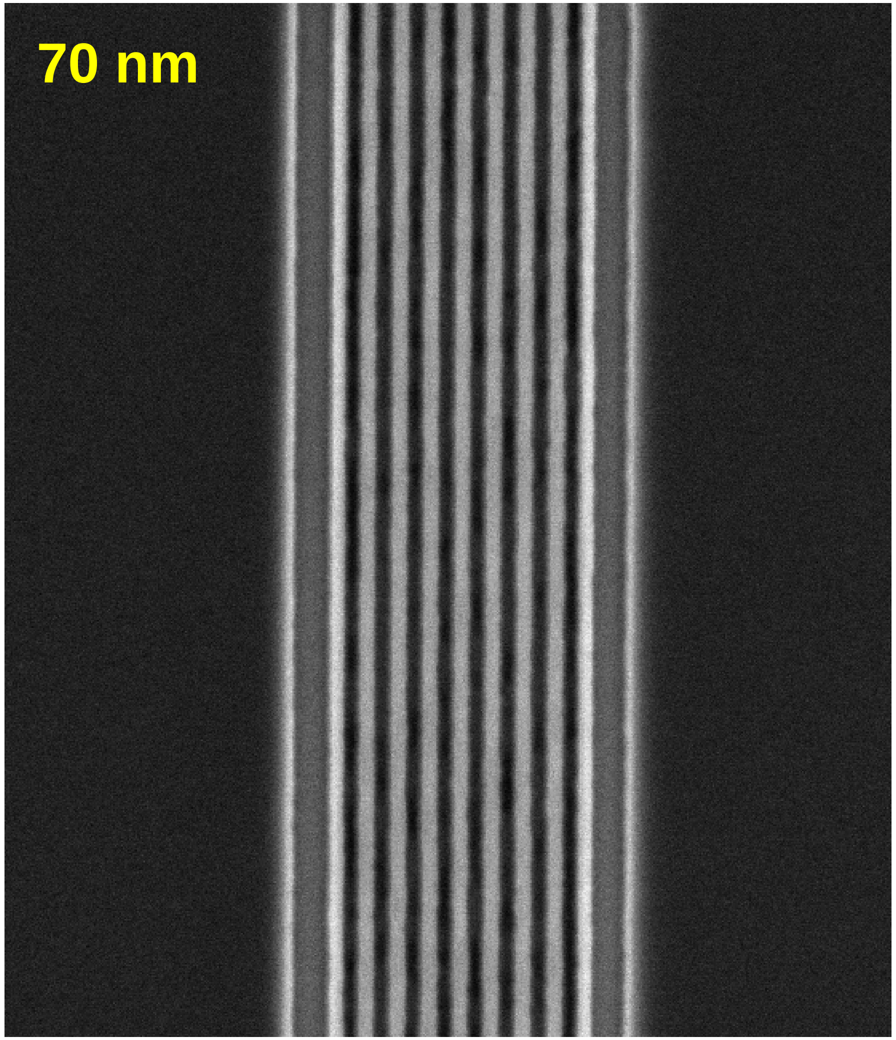
-1 diffracted order from right pole

+1 diffracted order from left pole

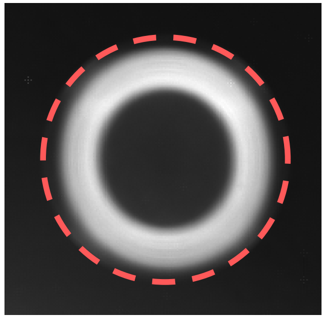
Dipole illumination enhances resolution in only one direction

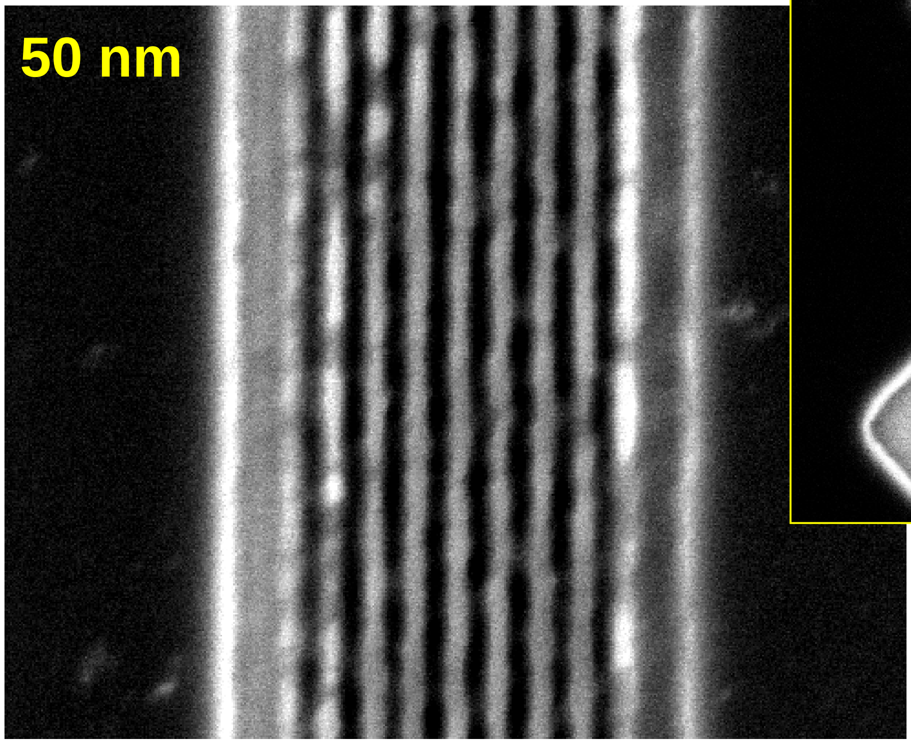


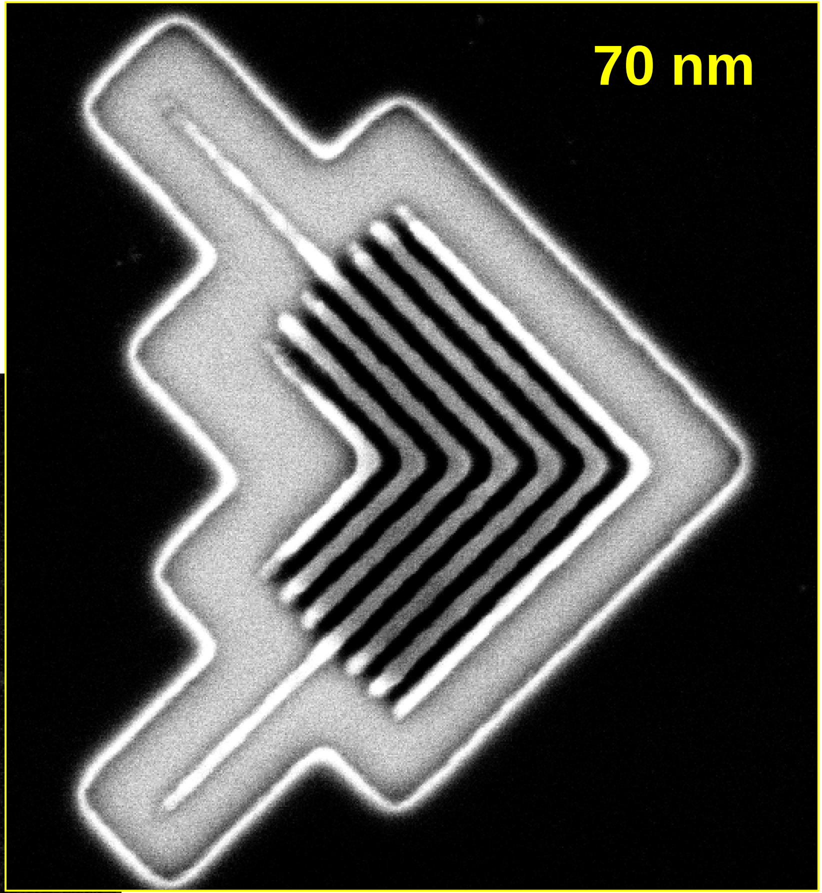




Annular illumination enhances resolution isotropically at the cost of effectiveness





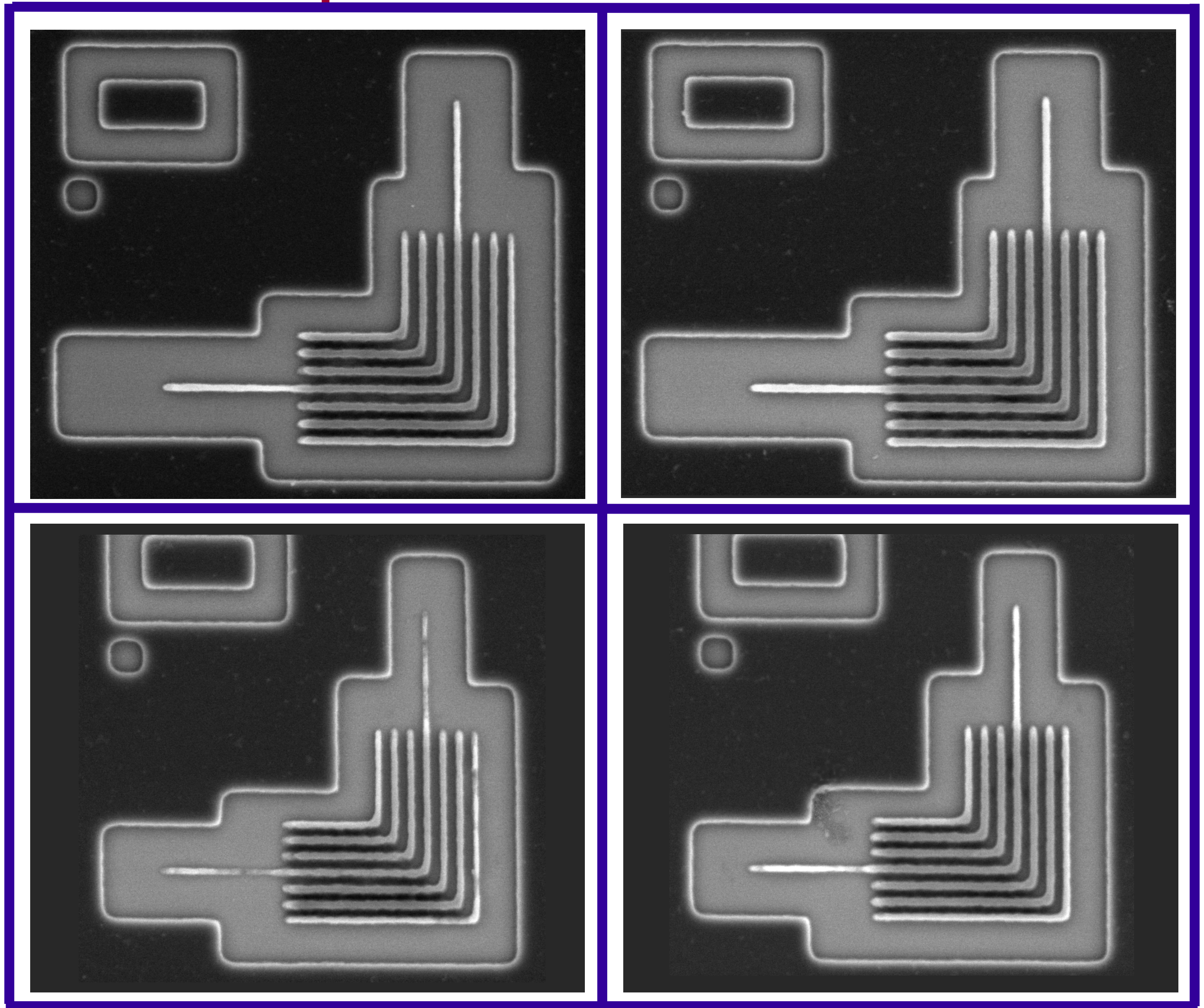


Programmable illuminator enables modeling of esoteric systems

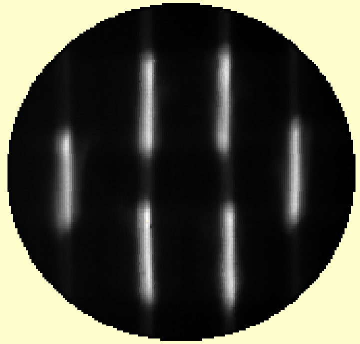
6-Stripe fill | Disk fill

80 nm

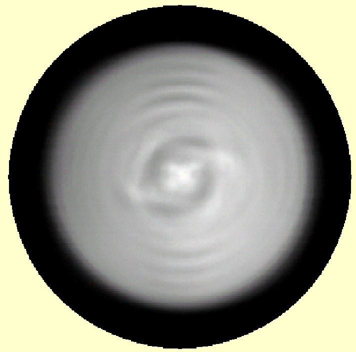
70 nm



6-Stripe Fill

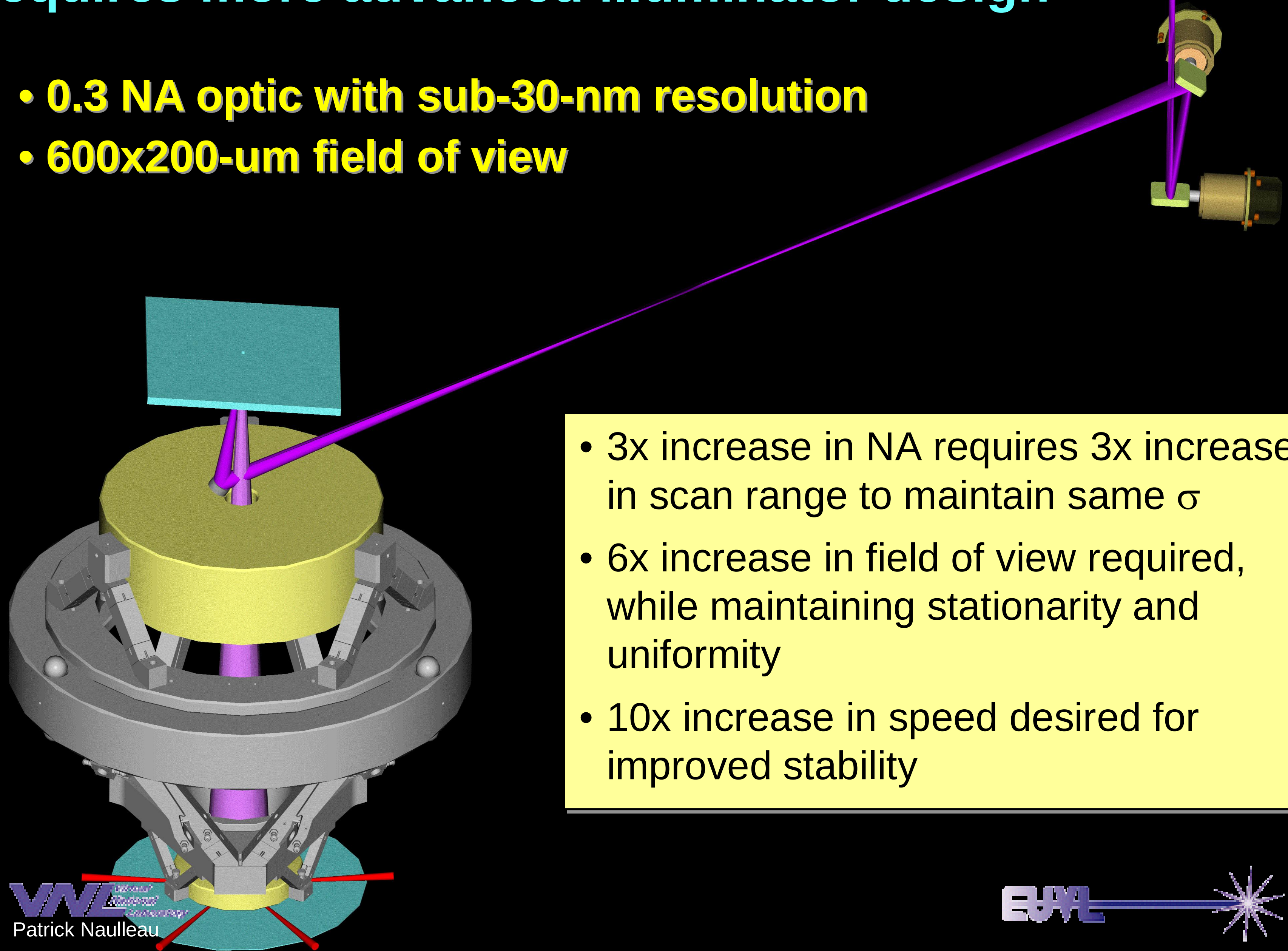


Disk σ = 0.8



Next-generation EUV lithography station requires more advanced illuminator design

- 0.3 NA optic with sub-30-nm resolution
- 600x200-um field of view



- 3x increase in NA requires 3x increase in scan range to maintain same σ
- 6x increase in field of view required, while maintaining stationarity and uniformity
- 10x increase in speed desired for improved stability

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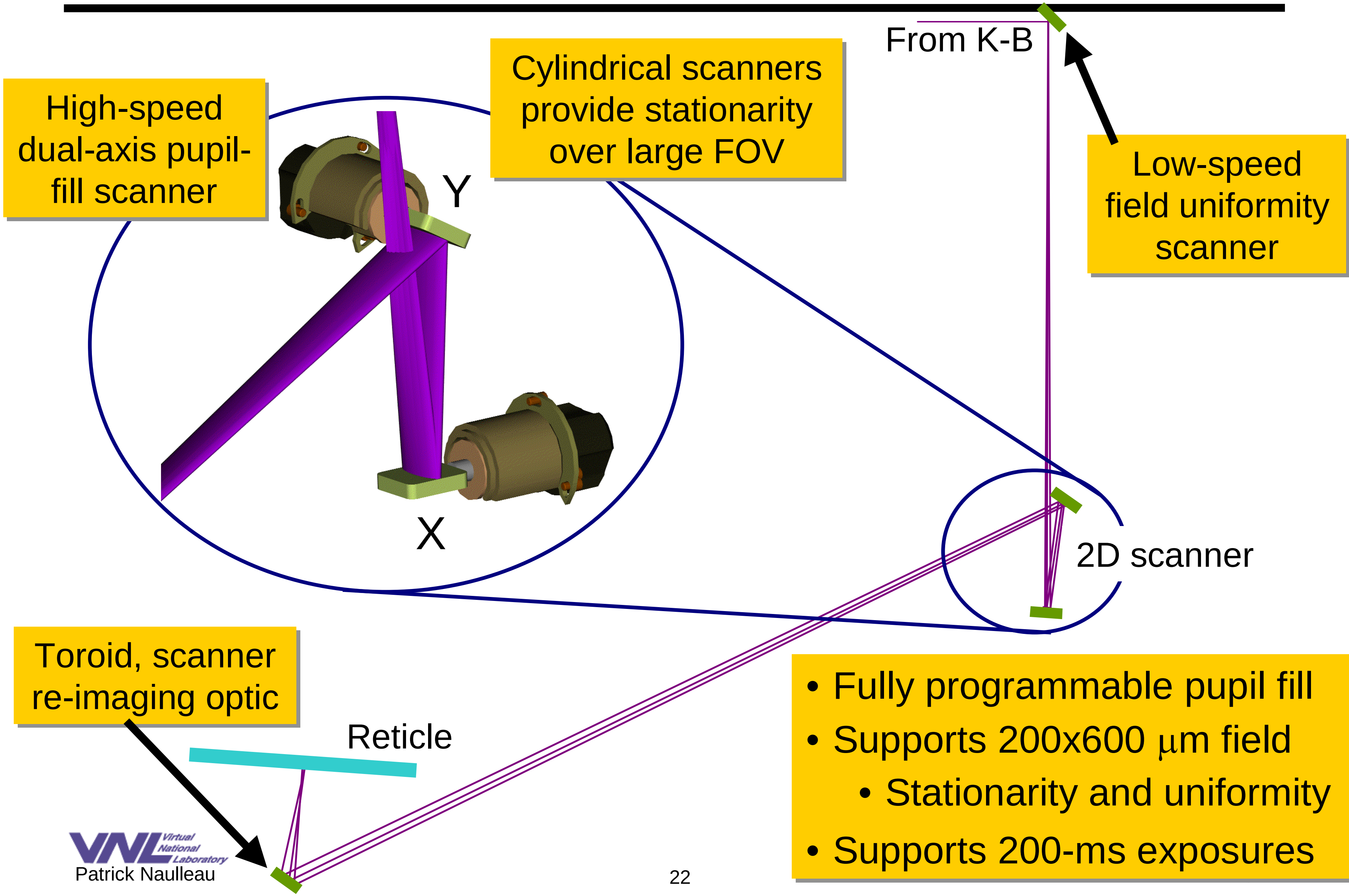
Multi-element cylindrical scanner meets design requirements



- Fully programmable pupil fill
- Supports 200x600 μm field
  - Stationarity and uniformity
- Supports 200-ms exposures

Summary

- Coherence control crucial to advanced imaging applications
- Scanning illuminators well-adapted to synchrotron use
- Effectiveness of scanning illuminator has been demonstrated through lithographic studies
  - 50-nm lines-space printing demonstrated with 0.1-NA optic
  - Programmable capabilities allow illumination to be tuned to pattern
- Scanning illuminator design extended to 0.3-NA optic

Acknowledgements

LBNL

Left to right: Patrick Naulleau, Dave Richardson, Rene Delano, Senajith Rekawa, Keith Jackson, Jeffrey Bokor, Ron Tackaberry, Kenneth Goldberg, Farhad Salmassi, Paul Denham, Brian Hoef, Drew Kemp, Phillip Batson, Gideon Jones

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